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J. R. Brophy, J. Mueller and D. K. Brown
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA

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John R. Brophy, * Juergen Mueller, ** and D. Kyle Brown†
Jet Propulsion Laboratory
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The ion accelerator system represents the key performance and life limiting component of ion engines. Carbon-carbon composite materials hold the promise of significantly improving the service life capability of ion accelerator systems due to their improved sputter resistance. Non-circular grid apertures are better suited to the physical structure of carbon-carbon composite materials because they allow fewer fibers to be cut resulting in grids with improved mechanical properties. Three accelerator systems were fabricated from flat, 14-cm diameter, carbon-carbon electrodes with long rectangular slots spanning the active grid diameter. Two two-grid accelerator systems and one three-grid accelerator system were tested. The perveance of the slotted grids were found to be the same as previously tested carbon-carbon accelerator systems with circular holes. The slotted grids were found to stand-off higher electric fields, up to 2870 V/mm, enabling beam current as high as 900 mA to be extracted. The charge-exchange ion erosion pattern of the slotted grids may facilitate improved grid life. Three-grid carbon-carbon accelerator systems may have more than twenty times the life of two-grid molybdenum systems.

Introduction

One of the major life-limiting mechanisms for state-of-the-art, rare gas fueled, ion engines is sputter erosion of the ion accelerator system electrodes. Carbon-carbon composite electrodes hold the promise of enabling a substantial increase in ion accelerator system service life capability because of their much higher resistance to sputter erosion than the currently used molybdenum grids, The first generations of carbon-carbon grids[1,2,3] used conventional arrays of circular holes in a hexagonal pattern. 'his was a natural evolution from molybdenum grids, but was not the best synergy with the basic characteristics of the composite material. Circular holes in a hexagonal pattern cut through most of the carbon fibers in the composite material significantly reducing its strength. In addition, delamination of the outer plies of the composi (e appears to be more likel y at locations where the webbing is the thinnest and is oriented normal to the direction of the fibers in the outermost plies. [4]

Mueller, et al., [5] first suggested the use of non-circular holes for carbon-carbon electrodes as a means to reduce fabrication costs, The use of non-circular apertures results in fewer holes and consequently lower costs. It also provides structural benefits. For the same open area fraction, Mueller pointed out, grids with non-circular holes can have more webbing material between the holes resulting in structurally stronger electrodes. Alternatively, for the same webbing material dimensions, non-circular holes enable the fabrication of higher open area fraction grids.

This paper describes the design, fabrication and testing of 14-cm diameter, flat, carbon-carbon electrodes with non-circular holes. In this case the non-circular apertures take the form of long slots which extend clear across the active grid. The resulting webbing material pattern is reminiscent of the wire grids used on Kaufman's original ion engine.[6] Test results for two- and three-grid configurations of these "slotted" grids are presented.

*Supervisor, Advanced Propulsion Technology Group, Member Al AA
**Member of the Technical Staff, Advanced I'repulsion Technology Group, Member AIAA
't'Member of the '1'ethnical Staff, Space Material Science Section, Member AIAA

Grid Design

Flat carbon-carbon grid blanks were fabricated with a fiber orientation designed to maximize the final grid strength. To accomplish this required a design which maximized the number of continuous, uncut carbon fibers in the grid. For the slot aperture configuration, this required that most of the fibers run along the direction of the slots.

The grid blanks were fabricated from 9 plies of unidirectional tape comprised of low-modulus graphite fibers. Two thirds of the plies were oriented with their fibers running along the intended slot direction which is designated the 0° direction. The other plies were orientated at 90 degrees to this direction (the 90° direction). The resulting panels have both a symmetric and balanced lay-up in order to maximize the likelihood that the panels will be flat (within 50 pm) after fabrication. Graphitization of the lay-up greatly improves the modulus of the graphite fibers and the overall mat erial.

Extremely good mechanical properties were obtained with this design as shown in l'able 1. In the direction parallel to most of the fibers the grid panels are as stiff in bending as molybdenum. The price for the high stiffness in this direction is that the panels are quite flexible in the direction normal to this.

Table 1 Mechanical Properties of Grid Blanks

Property	Value
Density	1.89 g/cm^3
Fiber Volume	50 %
Resin Volume	10%
CVD Volume	31 %
Void Volume	9 '?40
Average Tensile Strength: 0° Direction	755 MPa
Average Tensile Strength: 90° Direction	414 MPa
Average Tensile Modulus: O" Direction	230 GPa
Average Tensile Modulus: 90(' Direction	121 GPa
Flexural Strength: 0° Direction	289 MPa
Flexural Strength: 90° Direction	50 MPa
Flexural Modulus: 0° Direction	341 GPa
Flexural Modulus: 90° Direction	21 GPa

Four 14-cm diameter carbon-carbon slotted electrodes were fabricated. The geometries of the accelerator systems based on these grids arc given in 'l'able 2. The apertures were formed using a wire electric discharge machining (EDM) process. Each grid is comprised of only 51 slots, which makes them much easier to fabricate than machining **4,268** circular holes in the same sized grid, The slot geometries were selected so that the width of the screen grid slots is the same as the diameter of circular screen grid holes used in state-of-the-art mol ybdenum grids (1.91 mm). The slot configuration, however, results in a significantly higher physical open area fraction of 0.75 compared to 0.67 for the circular holes. It is expected that the higher open area fraction will result in lower screen grid erosion because fewer ions directed toward the accelerat or system w ill be intercepted by the screen grid.

The slot width for the accelerator grids in Grid Sets 1 and 3 was selected to be the same as that for the hole diameter of a typical SHAG (small hole accelerator grid), i .e. 1.14 mm. This, however, results in an open area fraction of the slotted accelerator grid of 0.45 as opposed to 0.2.4 for the circular holes. The high open area fraction is expected to result in relatively good accelerat or system performance (i.e. good perveance), but may result in lower discharge chamber performance (because of increased neutral propellant losses through the grids). The accelerator grid for Grid Set 2 was designed to give the same accelerator grid open area fraction as a conventional SHAG system (0.24). To accomplish this required a slot width of 0.76 mm. A diagram of the slot pattern is given in Fig, 1.

Apparatus and Procedure

The slotted carbon-carbon grids were tested on two ion sources of the segmented ion engine.[7] Only one ion source was operated at a time during data collection.

Tests were performed in a 2.4-m diameter by 5.5-m long stainless steel vacuum chamber equipped with oil diffusion pumps. "l'he pumping speed on xenon is approximately 14,000 1,/s. Vacuum chamber pressure measurements were made with an ion gauge calibrated directly on xenon. Typical vacuum chamber pressures during engine operation were 1.3 to 2.7x10-3 Pa (1 to $2x10^{-5}$ ton). The no-load pressure in the vacuum chamber is less than 4x 10"s Pa (3 x 10-7 torr).

The propellant feed system and power supply configuration are described in **Ref. 8.** Thermal mass flow meters were used in these tests to measure the xenon flow rates to the engine.

Table 2 Description of Carbon-Carbon Accelerator Systems

Item	Grid Set 1	Grid Set 2	Grid Set 3	Grid Set 4
Active Grid Diameter (cm)	14	14	14	15
Aperture Shape	Slots	slots	slots	Circular
Number of Apertures per Electrode	5]	51	51	4268
Screen Grid				
Thickness (mm)	**0,46**	0,46	0.46	0.44
Slot Width or Hole Diameter (mm)	**1.91**	1.91	1.91	1.93
Center-to-Center Slot or Hole Spacing (mm)	**2.42**	2.42	2.42	2.21
Minimum Grid Webbing Thickness (mm)	0,51	0.51	0.51	0.28
Open Area Fraction	0.75	0.75	0.75	0.67
Accelerator Grid				
Thickness (mm)	0,46	0.46	0.46	0.93
Slot Width or Hole Diameter (mm)	1.14	0.76	1.14	1.15
Center-to-Center Slot or Hole Spacing (mm)	2,42	2.42	2,42	2.21
Minimum Grid Webbing Thickness (mm)	1.28	1.66	1.28	1.07
open Area Fraction	0,45	0.24	0.45	0.24
Decelerator Grid				
Thickness (mm)	N/A	N/A	0.46	0.94
Slot Width or Hole Diameter (mm)	N/A	N/A	1.91	1.72
Center-to-Center Slot or Hole Spacing (mm)	N/A	N/A	2.42	2.21
Minimum Grid Webbing Thickness (mm)	N/A	N/A	0.51	0.49
Open Area Fraction	N/A	N/A	0.75	0.55
Screen -- Accelerator Grid Gap (mm)	0.61	0.61	0.61	0.64
Accelerator -- Decelerator Grid Gap (mm)	N/A*	N/A*	0.25	0.25

*Grid Set 1 and 2 are 2-grid accelerator systems.

Results

When the grids were received after the EDM machining process used to form the slots, close examination revealed numerous loose fibers and fiber bundles, Wiping the grid with a paper towel soaked in acetone removed most of these loosely held fibers. Roth sides of each grid were then lightly sanded by hand,

initial application of the high voltages was performed at high vacuum with the discharge off and no xenon flow. l-he screen voltage was increased in a step-wise fashion and was accompanied by frequent arcing with each voltage increase. At each voltage level the arcing then subsided, presumably as all of the potential breakdown initiation sights were removed by arcs. Eventually, the desired electric field stresses could be reached with the grids cold.

The perveance of the three-grid slotted accelerator system (Grid Set 3) is compared to that obtained with a three-grid carbon-carbon accelerator system with circular holes (Grid Set 4) in Fig. 2. For beam currents of 400 and 500 mA the minimum total voltage for the slotted grids is essentially the same as that for the circular hole grids. This is significant in view of the fact that the total active area of the slotted grids is only 87% that of the circular hole grids,

The maximum electric field between the screen and accelerator grid is higher for the slotted grids than for the circular hole grids: 2820 V/mm compared to 2450 V/mm. The higher electric field enables the slotted grids to extract a higher total current, and beam currents as high as 900 mA have been extracted. It is difficult to extract more than about 600 mA of ion current from the circular hole grids.

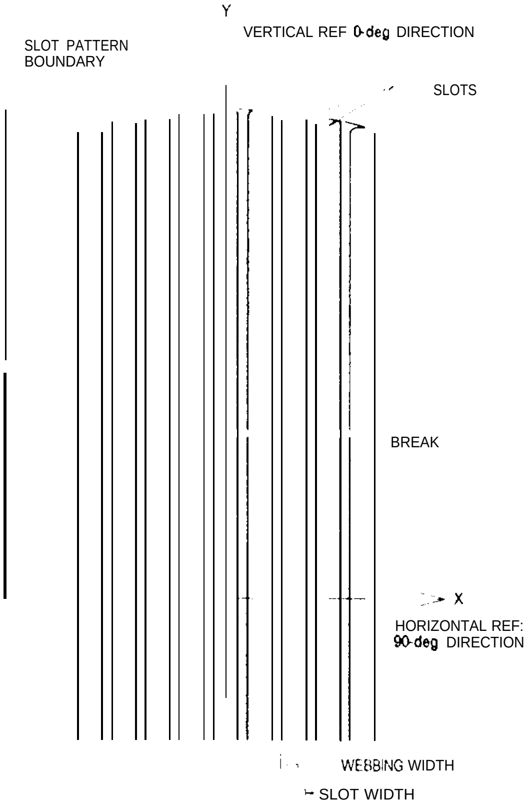

Fig. 1 Slot pattern for slotted carbon-carbon grids.

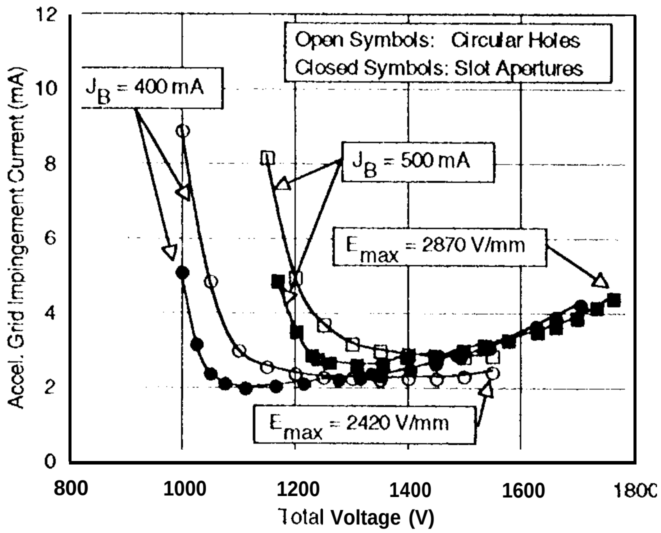

Fig. 2 Comparison of perveance for carbon-carbon grids with circular apertures (Grid Set 4) and slotted grid apertures (Grid Set 3) for beam currents of 400 and 500 mA.

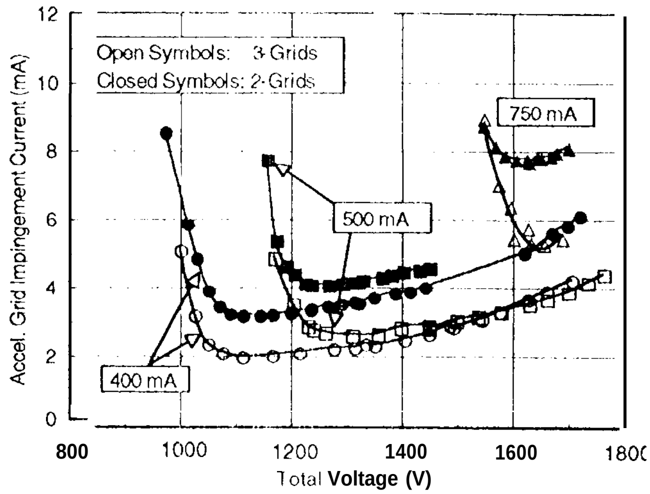

Fig. 3 Comparison of perveance for 2- and 3-grid carbon-carbon grids with slot apertures at beam currents of 400, 500 and 7S0 mA.

One unusual feature of these data for the slotted grids is that the variation of accelerator grid current, J_A, with total voltage has a minimum and increases to the right of this minimum. The reason for this is not clear, but is likely due to direct ion impingement. The three-grid system with circular holes exhibits a much flatter variation of J_A with increase total voltage to the right of the perveance limit, and it also has a much less sharp] y defined perveance limit.

The perveance for 2- and 3-grid slotted accelerator systems (Grid Sets 1 and 3) are compared in Fig. 3 for beam currents of **400, 500 and 750** mA. These data show that the addition of the decelerator grid has little effect on the perveance of the accelerator system. The decelerator grid does, however, reduce magnitude of the accelerator grid current for a given total voltage.

The variation of the accelerator and decelerator grid currents for Grid Set 3 is given in Fig. 4 for operation at a beam current of 500 mA. The decelerator grid current is seen to decrease with decreasing total voltage over the entire range. The relatively high decelerator grid currents at high total voltages almost certainly must be due to direct ion impingement, but no simulations of this have yet been performed to confirm this. The accelerator system was not operated long enough at this condition to produce obvious physical evidence of this direct ion impingement. Operation at other beam currents showed similar behavior for the decelerator grid current.

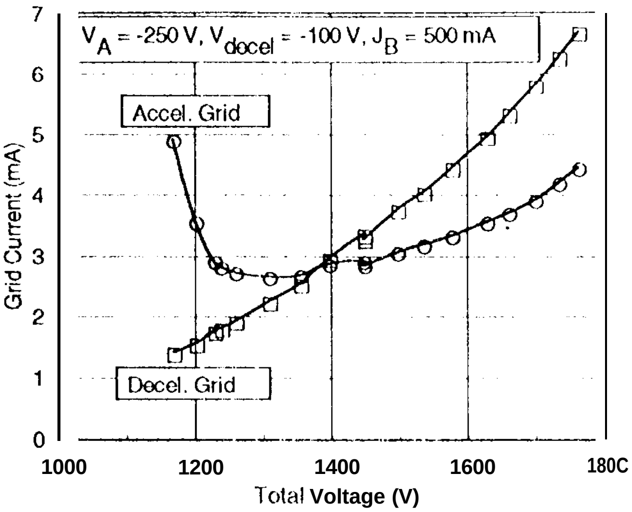

Fig. 4 Variation of accelerator and decelerator grid current with total voltage (Grid Set 3).

Although the perveance obtained with Grid Set 2, which has very narrow accelerator grid slots, has not yet been fully quantified it appears to have significantly lower beam extraction capabilities than that of Grid Set 1.

Improved beam extraction capability can be obtained by reducing the screen to accelerator grid gap. The data of Fig. 5 show the results of reducing this gap from 0.64 to 0.51 mm on Grid Set 4 (circular apertures) for beam currents of 400, 450 and 500 mA. The minimum total voltage required to extract a given beam current level is reduced by approximately 100 V. The maximum electric field is essentially unchanged (2450 V/mm at 0.51 mm compared to 2420 V/mm at 0.64 mm). Similar results may be expected for the slotted grids, although these data have" not yet been taken.

Grid Life Assessment

There are three features of the slotted, 3-grid, carbon-carbon, accelerator system tested herein which may significantly improve the service life of ion accelerator systems:

1. The improved sputter resistance of carbon-carbon.
2. The reduction in the magnitude of the applied accelerator grid voltage required to prevent electron backstreaming enabled by applying a negative voltage to the decelerator grid (i.e., SAND optics[8]).
3. The change in charge-exchange ion erosion patterns resulting from the use of slot apertures.

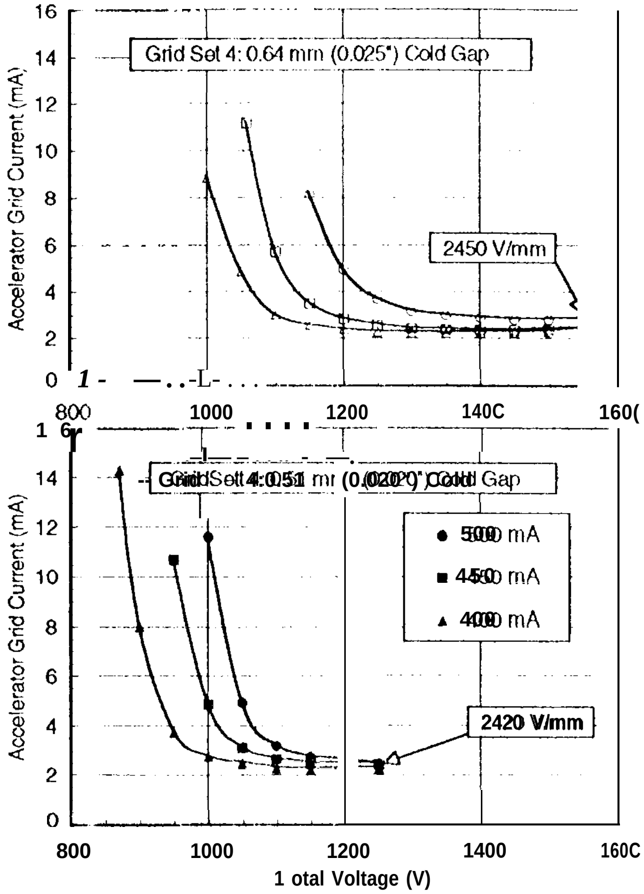

Fig. 5 Effect of screen -- accelerator grid gap on perveance for flat carbon-carbon grids with circular holes.

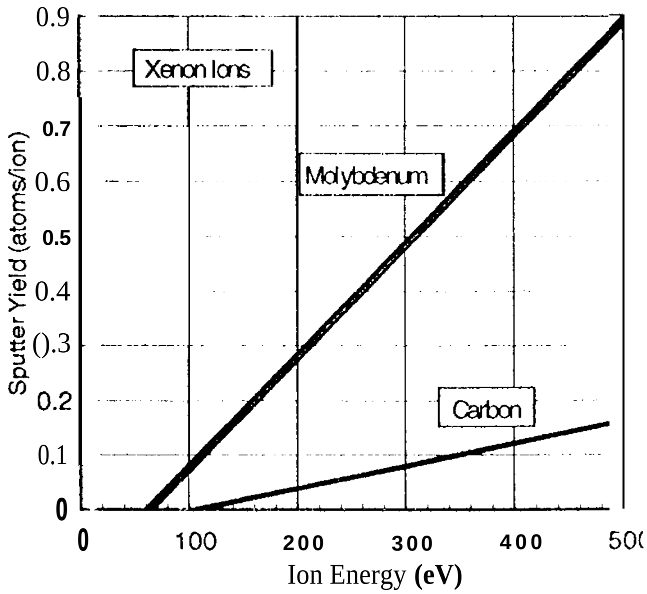

Fig. 6 Comparison of sputter yields for xenon ions on carbon (graphite) and molybdenum (Ref. 10).

The sputter yield[9] of carbon (graphite) is compared to that of molybdenum in Fig. 6. These data indicate, for example, that a carbon accelerator grid at a voltage of -350 V will result in the same sputter yield as a molybdenum grid at -120 V. Alternately, if both grids are at the same voltage, -200 V for example, then the carbon grid will have a sputter yield 7.5 times lower than the molybdenum grid. Due to the differences in densities, the carbon grid erosion rate should be even lower, almost one tenth the erosion rate of the molybdenum at this energy. Furthermore, Blandino, et al.[10], have shown that the sputter yields and erosion rates of carbon-carbon composites are close to those of graphite.

The use of a 3-grid SAND (Screen, Accelerator, Negative Decelerator) ion accelerator system can reduce the magnitude of the negative voltage that must be applied to the accelerator grid. It can also reduce the ion flux to the accelerator grid for operation in vacuum test facilities with background pressures above approximately 2x104 Pa (1 .5x 1 0^{-6} torr).

The effect of applying a bias of -100 V to the decelerator grid (relative to neutralize] common potential) for Grid Set 3 is compared to the operation of a 2-grid system (Grid Set 1) is given in Fig. 7 for a screen grid voltage of 1400 V. The top graph in this figure gives the minimum magnitude of the accelerator grid voltage, $|V_A|$, which prevents electron backstreaming. Operation at lower V_A than shown in Fig. 7 results in electron backstreaming. Clearly the minimum accelerator grid voltage is a function of the beam current extracted.

The maximum net-to-total accelerating voltage ratio (R-ratio) is also given in Fig. 7 for these data. Experience with the thicker carbon-carbon grids of Grid Set 4 with circular holes suggests that significantly higher R-ratios could be obtained with thicker accelerator and decelerator grids and with a decelerator grid with a smaller open area fraction than that used in Grid Set 3.

The use of a negatively biased decelerator grid is shown in Fig. 7 to reduce the magnitude of the required accelerator grid voltage by 25 to 30 V. Even more significant effects are given in Fig. 8 for operation with a screen grid voltage of 1100 V. in this case, both curves are for operation with the 3-grid optics of Grid Set 3. The upper curve is for operation with a negative decelerator grid voltage of-125 V. The

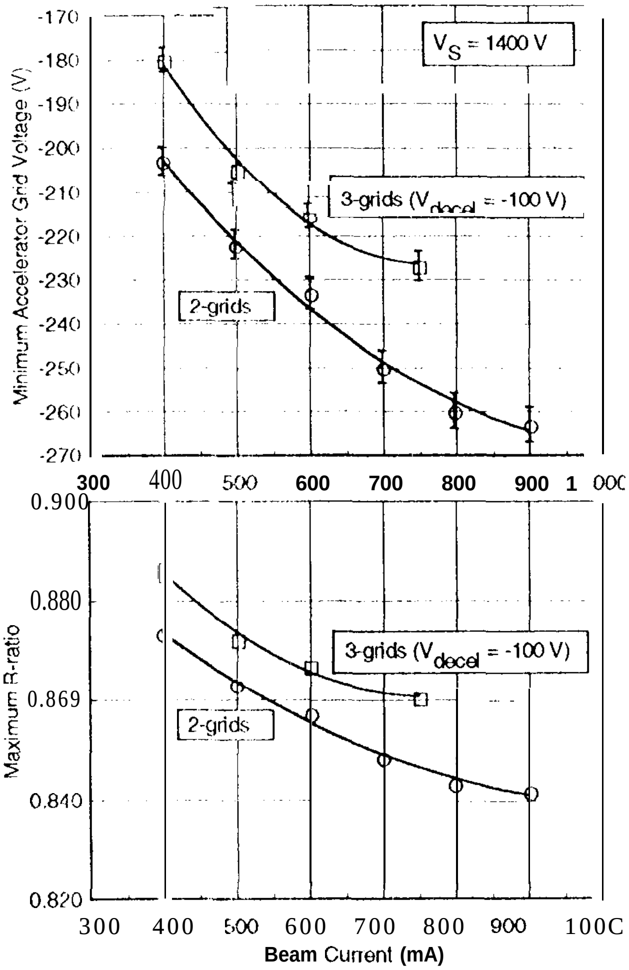

Fig. 7 Effect of SAND optics (Grid Set 3) on the minimum accelerator grid voltage required to prevent electron backstreaming compared to a 2-grid accelerator system (Grid Set 1).

lower curve is for operation with the decelerator grid at neutralizer common voltage. In this case the negative decelerator grid bias has enabled the magnitude of the accelerator grid voltage to be reduced by about 70 V.

This is roughly a 35% reduction in accelerator grid voltage. From Fig. 6, reducing the magnitude of the accelerator grid voltage from -200 to -130 V will result in almost a factor of 4 reduction in the sputter yield for a carbon grid (assuming the extrapolations of the sputter yield to low ion energies as given in Fig. 6 are correct). Even more significantly, a carbon-carbon accelerator grid operating at a voltage of -130 V will have a sputter yield almost a factor of 25 less than a molybdenum grid at -180 V.

The full power operating point for NASA's 30-cm diameter NSTAR[1] ion engine has a beam current

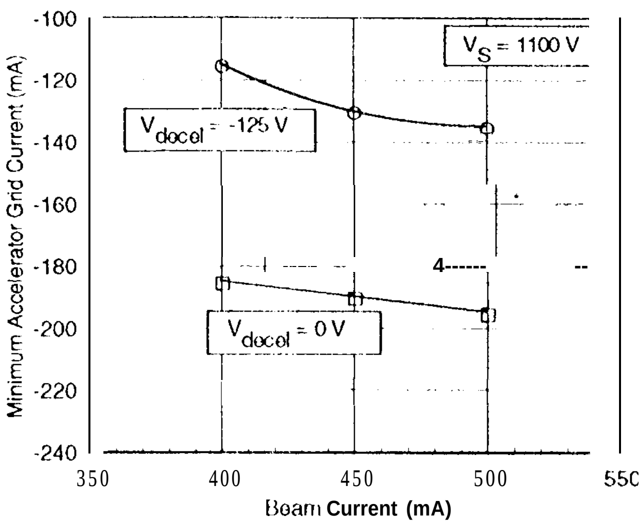

Fig. 8 Effect of negative decelerator grid voltage on the minimum required accelerator grid voltage required to prevent electron backstreaming for Grid Set 3.

of 1,72 A at a screen voltage of 1100 V. This is equivalent to four 14-cm diameter ion sources operating at a beam current of 430 mA each, If these smaller ion sources were equipped with the 3-grid, flat, slotted, carbon-carbon accelerator systems described herein, the service life of the accelerator grid may be increased by more than a factor of twenty. Screen grid erosion may also be reduced due to the higher open area fraction of the slot geometry and the sputter resistance of carbon-carbon,

The charge-exchange (CEX) ion erosion pattern on the accelerator grid of a 2-grid system with long rectangular slots will be different from that obtained on grids with circular apertures. With long slots, the CEX pattern appears to form a trench down the center of the webbing between each pair of slots. Erosion of these trenches completely through the webbing should not affect the operation of the accelerator system. Even if the trenches erode through the webbing along the entire length of the slot there should be no affect on the integrity of the accelerator grid.

The reason for this is that these trench erosion patterns do not connect with each other. But rather, the erosion pattern tends to become diffuse at the outer edges of the slots insufficient operating time with the slotted grids has been obtained to determine what the failure mechanism due to CEX erosion will be. The erosion patterns for 3-grid accelerator systems will, of course be different, but the CEX erosion on the decelerator grid, especially in the SAND optics, is similar to that for the accelerator grid in 2-grid systems,

Future Design Improvements

One disadvantage of the slotted geometry is that the open area fraction of the accelerator grid is significantly larger than for grids with circular apertures even if the slot width is the same as the hole diameter. The experience with Grid Set 2 suggests that uniformly reducing the slot width appears to be an unsatisfactory approach to reducing the accelerator grid open area fraction.

However, the slots could easily be machined so that their width was a function of radial position from the center of the grids. For example, the slot going through the center could have a maximum width of 1,14 mm and then taper off to a width of 0.76 mm at both edges of the grid. Slots not going through the center of' the grid would have maximum widths which decrease with increasing distance from the center, and then taper off to 0.76 mm at the edges. The slots farthest from the center would be a uniform 0.76 mm wide,

other potential improvements include increasing the thickness of the accelerator and decelerator grids and reducing the open area fraction of the decelerator grid. These changes should facilitate operation at higher R-I atios than those obtained with Grid Set 3.

Conclusions

The use of circular apertures in a hexagonal pattern results in most of the carbon fibers in a carbon-carbon composite grid being cut. An approach which is more synergistic with the inherent properties of carbon-carbon composites makes use of elongated or slotted apertures. Special grid blank panels were fabricated to maximize the number of **uncut** fibers in a grid configured with slots extending completely across the active grid region.

Carbon- carbon grids with long rectangular slots instead of circular apertures are easier and less expensive to machine, easier to align, and enable operation at higher electric field stresses and higher beam currents. The accelerator grid in three grid configurations of flat, slotted, carbon-carbon electrodes may have more than twenty times the service life of 2-

grid molybdenum systems. Easily implemented design improvements such as tapering the slot width and increasing the thickness of the accelerator and decelerator grids may further improve the performance and service life capability of carbon-carbon grids.

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